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## CONTRACT TECHNICAL NOTE

# A NUMERICAL INVESTIGATION OF THE VALIDITY OF THE BORN APPROXIMATION FOR DETERMINATION OF THE REFLECTION COEFFICIENTS OF UNDERDENSE PLASMA SLABS

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## GM DEFENSE RESEARCH LABORATORIES

SANTA BARBARA, CALIFORNIA

AEROSPACE OPERATIONS DEPARTMENT

CTN64-08

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## CONTRACT TECHNICAL NOTE

# A NUMERICAL INVESTIGATION OF THE VALIDITY OF THE BORN APPROXIMATION FOR DETERMINATION OF THE REFLECTION COEFFICIENTS OF UNDERDENSE PLASMA SLABS

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## ABSTRACT

The validity of the Born approximation for determination of
the reflection coefficients of plasma slabs is numerically
examined for two cases: the uniform underdense plasma slab
and a plasma slab with a sinusodial electron density perturb-
ation superimposed on a constant electron density. The regions
of validity of the Born approximation are discussed in each case.

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## I. INTRODUCTION

In the study of the propagation of electromagnetic waves through ionized gases it is seldom possible to get analytic solutions which are easy to interprete without tedious computing. Direct numerical solutions give accurate results, but they also fail to give physical insight into the mechanism of propagation. However, sometimes it is desirable to have an analytic solution which is easy to follow even if some accuracy has to be sacrificed.

The Born approximation, applied to the problem of EM scattering from an underdense plasma, serves this purpose. To use the Born approximation one has to assume that the incident wave is not changed by the medium through which it passes, and to neglect multiple scattering. It has been used often and, for example, Booker and Gordon[1]* have used it successfully to solve the problem of scattering from small random inhomogeneities in the troposphere. A good discussion of the Born approximation is given in Schiff[2] and other textbooks on quantum mechanics and wave propagation.

In this note, the Born approximation is used to derive the transmission and reflection coefficients of uniform and nonuniform plasma slabs for normal incidence. It is shown that the Born approximation gives very good results for the reflection coefficient of uniform slabs (within 8% up to plasma frequencies of 0.2 of incident frequency and slab thicknesses up to five wavelengths of incident wave). The transmission coefficient, calculated from the Born approximation, has a magnitude greater than unity but its phase shift is approximately correct. The reflection coefficient for a plasma in which there are harmonic variations in electron density is also calculated and compared with the exact results.

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* Raised numbers in parentheses indicate references listed at the end of this report.

In this latter case the errors in the Born approximation are due mostly to the scattering from the outside boundaries of the plasma. It should be mentioned that a strong resonance occurs in the case when the wavelength of the fluctuations is exactly equal to one-half of the free-space wavelength. This result can be useful in studying the reflection from the turbulent wakes of hypersonic projectiles — a subject which will be treated in a subsequent note.

## II. THEORY

### Reflection and Transmission of EM Waves from Nonuniform Underdense Plasma Slabs

Let a plasma be confined to a slab of thickness d, located such that the z-axis is perpendicular to the slab, as depicted in Figure 1. Let a plane transverse electromagnetic wave propagating in the direction of the positive z-axis with its electric field $E_i$ in the x direction be incident on the plasma slab. The electric field is given by

Figure 1  Geometry of the Plasma Slab

$$E_i = 1_x E_o \exp\left[ j(\omega t - kz) \right] \tag{1}$$

where $E_o$ is the complex amplitude of the incident wave, $\omega$ is the angular frequency of the wave, $t$ is the time, $k = 2\pi\lambda^{-1}$ and $\lambda$ is the wavelength of the wave in free space.

It will be assumed that the first Born approximation is valid, i.e., that the variations of $E_i$ can be neglected throughout the plasma and also that the multiple scattering can be neglected, hence the incident field is the total field

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throughout the plasma. It will also be assumed that the properties of the plasma change only in the z-direction.

A uniform layer of plasma of thickness a will have the reflection coefficient[3]

$$R = \frac{E_r}{E_i} = \frac{(1-\epsilon/\epsilon_0)\left[1-\exp(-2jk\sqrt{\epsilon/\epsilon_0}\,a)\right]}{(\sqrt{\epsilon/\epsilon_0}+1)^2 - (\sqrt{\epsilon/\epsilon_0}-1)^2\exp(-2jk\sqrt{\epsilon/\epsilon_0}\,a)} \qquad (2)$$

where $E_r$ and $E_i$ are the complex amplitudes of the reflected and incident electromagnetic waves, respectively, evaluated at the incident side of the slab, and $\epsilon$ and $\epsilon_0$ are the permittivity of the plasma and free space, respectively.

For an elementary slab of thickness $d\zeta$, located at $\zeta$, expression (2) reduces to (subscript "e" stands for "elementary")

$$R_e = \frac{\epsilon-\epsilon_0}{2\epsilon_0}\,jk\,d\zeta = -\frac{jk}{2}\,\Delta\,d\zeta \qquad (3)$$

where

$$\Delta \equiv \frac{\epsilon-\epsilon_0}{\epsilon_0} \qquad (4)$$

or, of one defines the reflection coefficient as the ratio of the reflected-wave amplitude to the transmitted-wave amplitude at the origin,

$$R_e = -\frac{jk}{2}\,\Delta e^{-2jk\zeta}\,d\zeta \qquad (5)$$

Within the validity of the Born approximation the reflection coefficient of the entire slab is

$$R = -\frac{jk}{2}\int_{\zeta=0}^{a}\Delta e^{-2jk\zeta}\,d\zeta \qquad (6)$$

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The transmission coefficient of a uniform plasma slab is

$$T = \frac{E_t}{E_i} = \frac{4\sqrt{\epsilon/\epsilon_0}\ \exp\left[-jk\left(\sqrt{\epsilon/\epsilon_0}-1\right)a\right]}{\left(\sqrt{\epsilon/\epsilon_0}+1\right)^2 - \left(\sqrt{\epsilon/\epsilon_0}-1\right)^2 \exp\left[-2jk\sqrt{\epsilon/\epsilon_0}\ a\right]} \tag{7}$$

where $E_t$ is the amplitude of the transmitted wave and $E_t$ and $E_i$ are evaluated at the same point. For infinitesimal thickness

$$T_e = 1 - jk\ d\zeta\left[\left(\sqrt{\epsilon/\epsilon_0}-1\right) - \frac{1}{2}\left(\sqrt{\epsilon/\epsilon_0}-1\right)^2\right] \tag{8}$$

Retaining only the first power in $\left(\sqrt{\epsilon/\epsilon_0}-1\right)$, (8) becomes

$$T_e = 1 - jk\left(\sqrt{\epsilon/\epsilon_0}-1\right)d\zeta \tag{9}$$

The change in the transmitted wave due to the elementary plasma slab is represented by the second term in the right-hand side in (9). The total transmission coefficient is hence

$$T_e = 1 - jk\int_0^a \left(\sqrt{\epsilon/\epsilon_0}-1\right)d\zeta \tag{10}$$

The phase shift in the transmitted wave is hence (for negligible losses, that is, pure real $\epsilon$)

$$\angle T = -\arctan k\int_{\zeta=0}^a \left(\sqrt{\epsilon/\epsilon_0}-1\right)d\zeta \approx -\arctan\frac{k}{2}\int_{\zeta=0}^a \Delta\,d\zeta \tag{11}$$

## III. DISCUSSION OF RESULTS

The magnitude of the transmission coefficient for real $\epsilon$ in the Born approximation is always greater than one, and, hence, physically meaningless. However, for small $\Delta$ (10) will give the phase shift with an accuracy which

will depend on the thickness of the medium and the magnitude of $\Delta$. Also (10) gives an indication that, at least for small $\Delta$, the angle of T depends only on the average properties of the medium.

The reflection coefficient (6) is a function of the changes of $\Delta$ throughout the plasma and, for small $\Delta$, the errors made by using (6) instead of the exact reflection coefficient are small. To illustrate this point, on Figures 2 to 4, the error

$$\epsilon = \left| \frac{R - R_a}{R} \right| 100 \tag{12}$$

where R is the exact value of the reflection coefficient for the uniform plasma and $R_a$ is computed from (6) assuming constant $\Delta$, is plotted. In a slightly ionized plasma[4]

$$\Delta = - \frac{\Omega_p^2}{1 - j\Omega_c} \tag{13}$$

where $\Omega_p^2 \equiv (q^2 n)/(\epsilon_0 m\omega^2)$, q is the charge of an electron, m is its mass, n is the electron density, $\Omega_c \equiv \nu_c/\omega$ and $\nu_c$ is the collision frequency between electrons and neutral atoms. It is seen that the error does not exceed a few percent for $\Omega_p \leq 0.2$ and $\Omega_c \leq 0.2$.

If the electron density has a periodic component, i.e., it can be expressed as

$$n = n_0 + n_1 \sin(k_1 z + \theta) \tag{14}$$

where $n_0 > n_1$ and $n_1$ and $k_1$ are constants, then, assuming constant collision frequency, $\Delta$ can be expressed as

$$\Delta = - \frac{\Omega_{po}^2}{1 - j\Omega_c} (1 + h \sin k_1 z) \tag{15}$$

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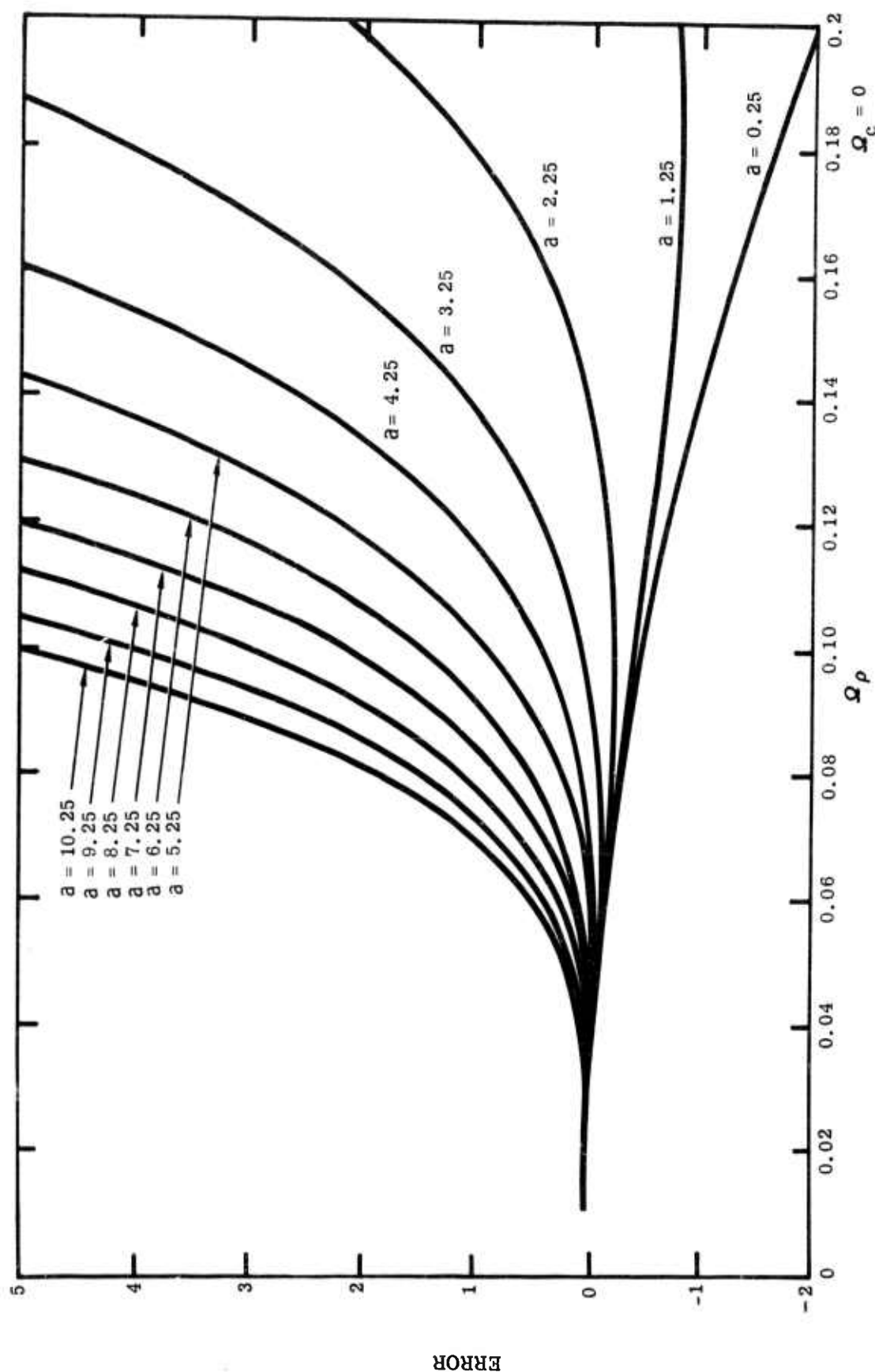
Figure 2  Percentage Error in Reflection Coefficient of Uniform Plasma Slab for Born Approximation as a Function of Normalized Plasma Frequency, Normalized Thickness of the Slab, and Normalized Collision Frequency $\Omega_c = 0$
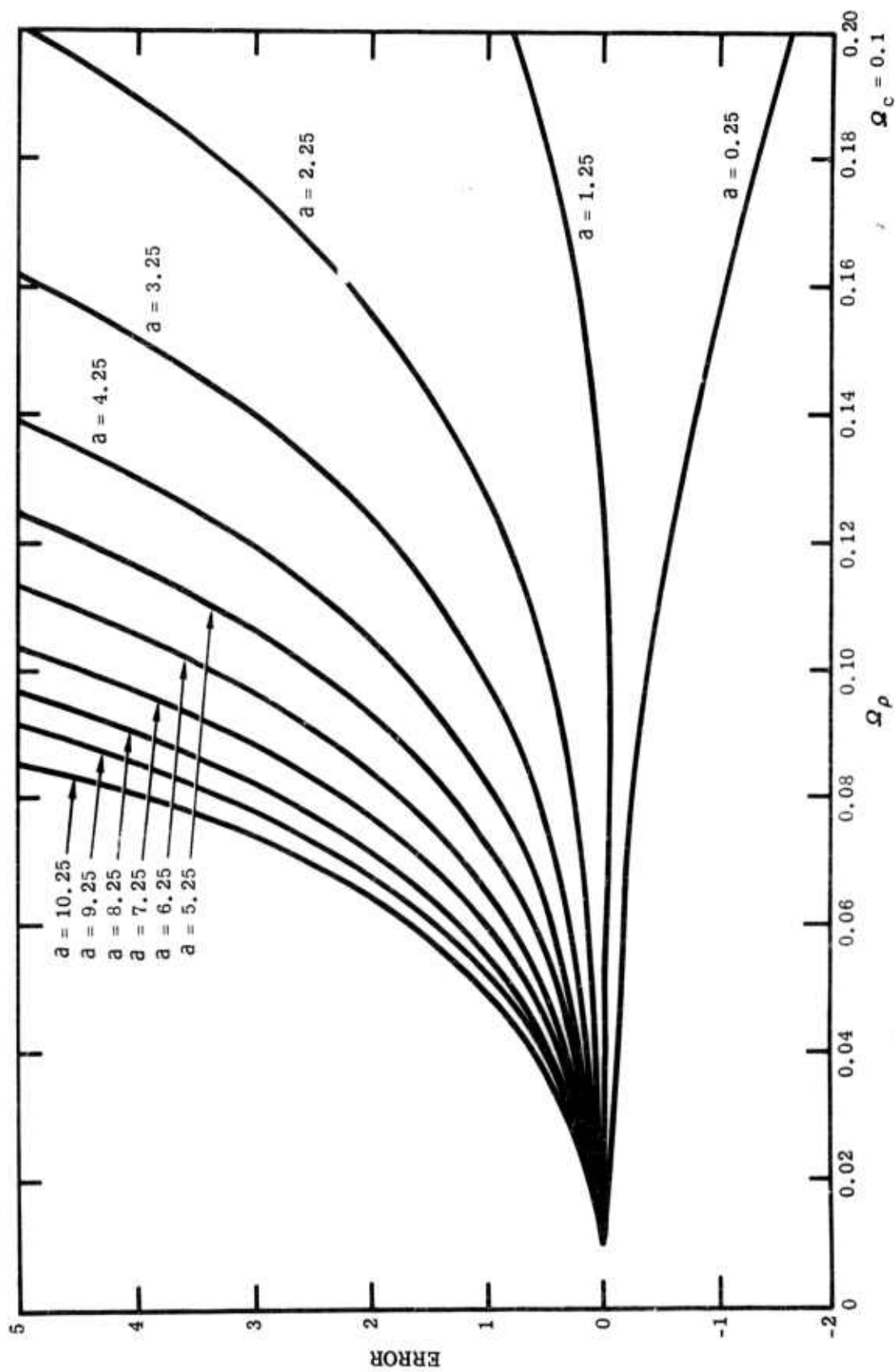
Figure 3  Percentage Error in Reflection Coefficient of Uniform Plasma Slab for Born Approximation as a Function of Normalized Plasma Frequency, Normalized Thickness of the Slab, and Normalized Collision Frequency $\Omega_c = 0.1$
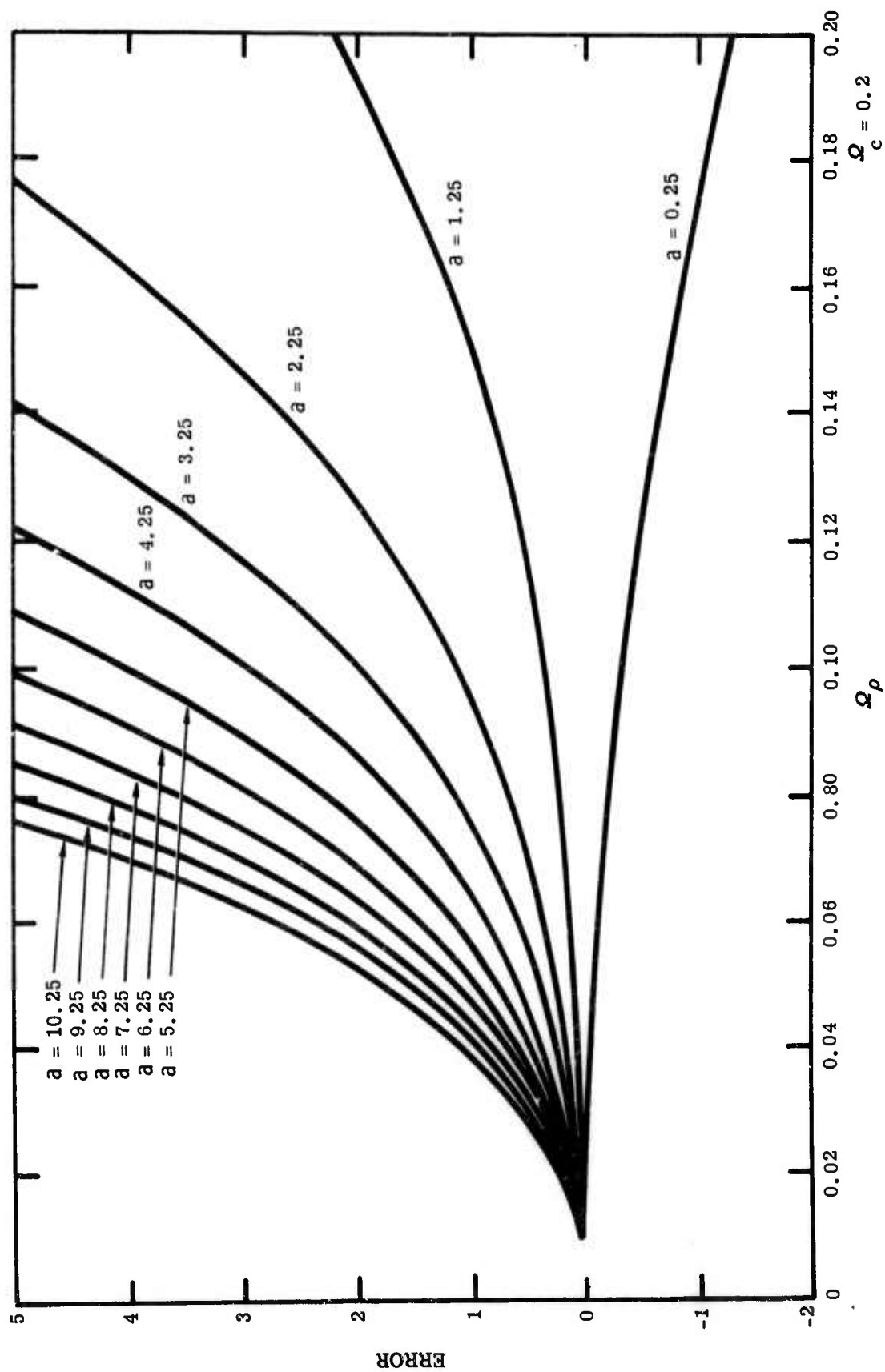
Figure 4   Percentage Error in Reflection Coefficient of Uniform Plasma Slab for
Born Approximation as a Function of Normalized Plasma Frequency,
Normalized Thickness of the slab, and Normalized Collision Frequency $\Omega_c = 0.2$

where $\Omega_{po}^2 = (q^2 n_o)(\epsilon_o m \omega^2)^{-1}$ and $h \equiv n_1/n$. Substituting expression (15) into (6) gives

$$R = \frac{k \Omega_{po}^2}{2j(1-j\Omega_c)} \int_{\zeta=o}^{a} (1 + h \sin k_1 \zeta) \, e^{-2j k \zeta} d\zeta \qquad (16)$$

Integrating, one has

$$R = \frac{\Omega_{po}^2}{4(1-j \Omega_c)} \left\{ \left[ 1 - e^{-j2ka} \right] + h \, (ka) \left[ \frac{e^{ja(k_1 - 2k)} - 1}{ja(k_1 - 2k)} + \frac{e^{-ja(k_1 + 2k)} - 1}{ja(k_1 + 2k)} \right] \right\} \qquad (17)$$

The first term on the right-hand side represents the Born approximation for the reflection from a uniform plasma, i.e., for $h=o$. The second term represents the contribution due to the periodicity of the plasma.

It is obvious that for $k_1 = 2k$ a strong resonance occurs. For $k_1 = 2k = 4\pi/\lambda$ expression (18) becomes

$$R = \frac{\Omega_{po}^2}{4(1-j \Omega_c)} \left\{ \left[ 1 - e^{-2kja} \right] + 2\pi h \, \frac{a}{\lambda} \left[ 1 + j \, \frac{1 - e^{-4jka}}{4ka} \right] \right\} \qquad (18)$$

and hence, a ripple in electron density equal to only 20% of the average electron density can enhance the reflection of the plasma ten wavelengths long by over six times (about 16 db in power).

Off resonance, the contribution of the harmonic part of the electron density decreases rapidly and fluctuates around the reflection coefficient for a uniform plasma.

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To illustrate the accuracy of the Born approximation, in Figures 5 to 11 the square of the magnitude of the reflection coefficient for the plasma with electron density distribution given by (14) is plotted versus the density wavelength $M = 2\pi/k_1$, as calculated from expression (17). Then, for $h = 0.2$ and $h = 1$ the exact values of reflection coefficient obtained by using an exact numerical technique[5] are given for comparison. It is seen that the agreement between the two curves is good and that the main difference comes from the uniform component of electron density (change of the effective thickness of plasma). Around the resonances $(M = 1/2)$ agreement is, for most practical purposes, very good. The vertical scale is expressed in decibels below the unity reflection coefficient because the square of the reflection coefficient as defined by (2) is the power reflection coefficient.

## IV. CONCLUSIONS

It is seen that, depending on the required accuracy, the Born approximation can be a very satisfactory approach for studying the reflections from underdense plasmas — up to plasma frequencies of about 0.2 of incident frequency. Its chief merit lies in its simplicity and ability to handle nonuniform plasmas.

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4. E.C. Jordan, Electromagnetic Waves and Radiating Systems, Prentice-Hall, Inc., 1950, p. 661

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Figure 5   Reflection Coefficient (Born Approximation) of a Plasma Slab with Harmonic Density Variation as a Function of the Normalized Density Wavelength and a Density Modulation  h = 0.05
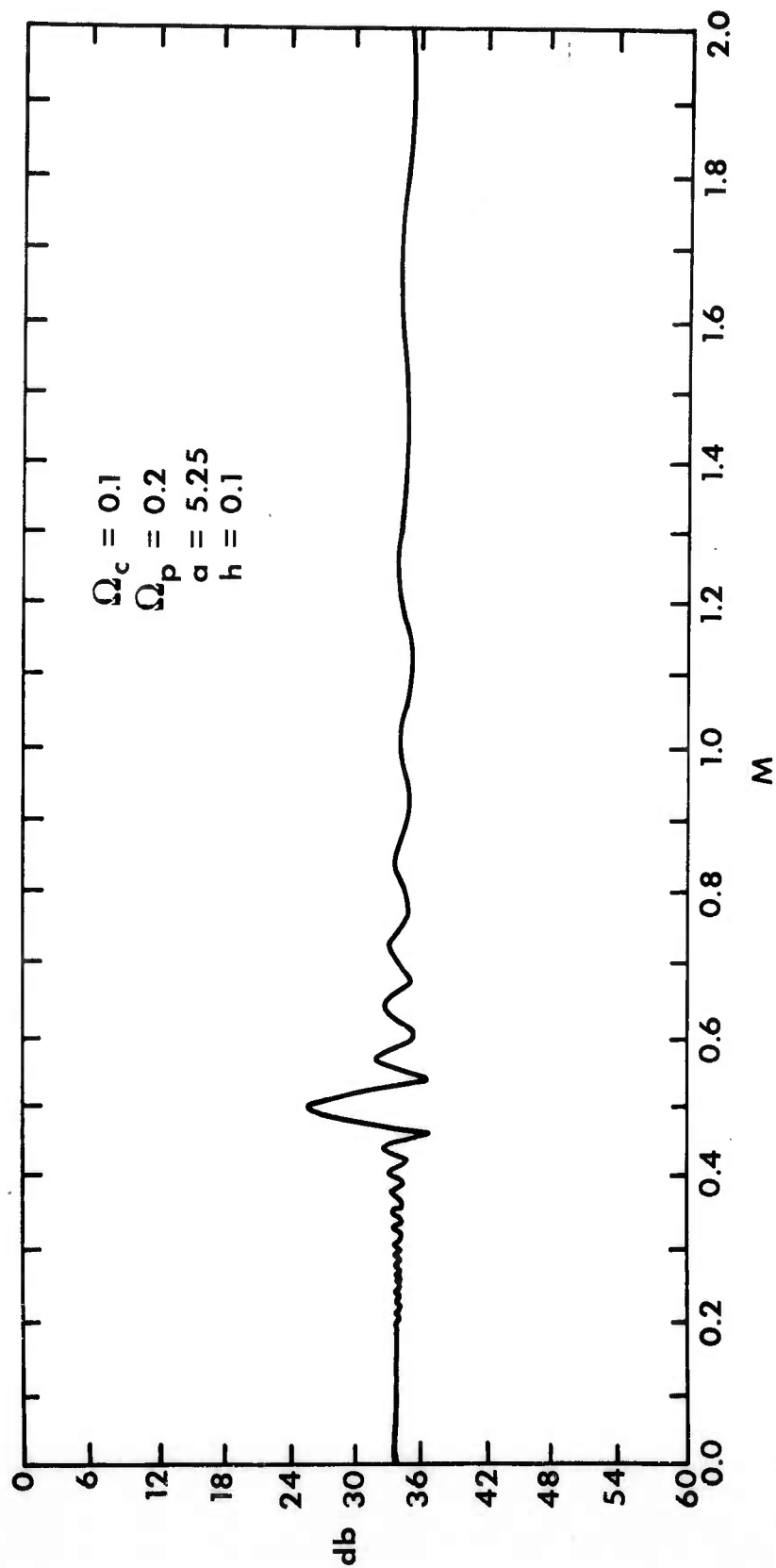
Figure 6 Reflection Coefficient (Born Approximation) of a Plasma Slab with Harmonic Density Variation as a Function of the Normalized Density Wavelength and a Density Modulation h = 0.1

Figure 7    Reflection Coefficient of a Plasma Slab with Harmonic Density Variation as a
Function of the Normalized Density Wavelength and a Density Modulation h = 0.2
Dashed Line  —  Exact Values of Reflection Coefficient
Solid Line   —  Born Approximation of the Reflection Coefficient

$\Omega_c = 0.1$
$\Omega_p = 0.2$
$a = 5.25$
$h = 0.2$

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Figure 8   Reflection Coefficient (Born Approximation) of a Plasma Slab with Harmonic Density Variation as a Function of the Normalized Density Wavelength and a Density Modulation h = 0.4

$\Omega_c = 0.1$
$\Omega_p = 0.2$
$a = 5.25$
$h = 0.4$

Figure 9  Reflection Coefficient (Born Approximation) of a Plasma Slab with Harmonic Density Variation as a Function of the Normalized Density Wavelength and a Density Modulation h = 0.6

Figure 10  Reflection Coefficient of a Plasma Slab with Harmonic Density Variation as a
Function of the Normalized Density Wavelength and a Density Modulation h = 1.0
and a = 5.25

Colored Curve:   Exact Values of Reflection Coefficient
Black Curve:   Born Approximation of the Reflection Coefficient
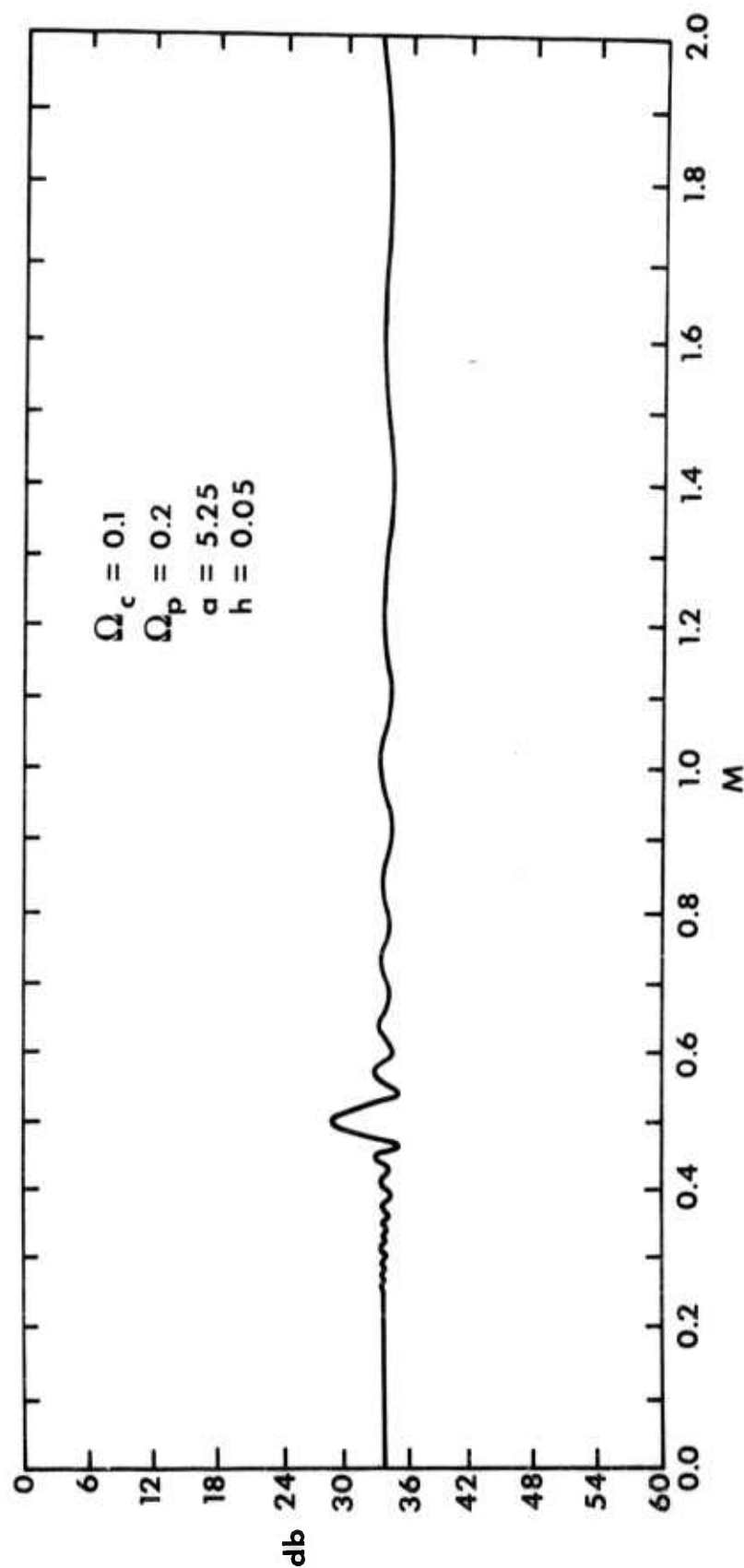
Figure 11   Reflection Coefficient of a Plasma Slab with Harmonic Density Variation as a Function of the Normalized Density Wavelength and a Density Modulation h = 1.0 and a = 5.5

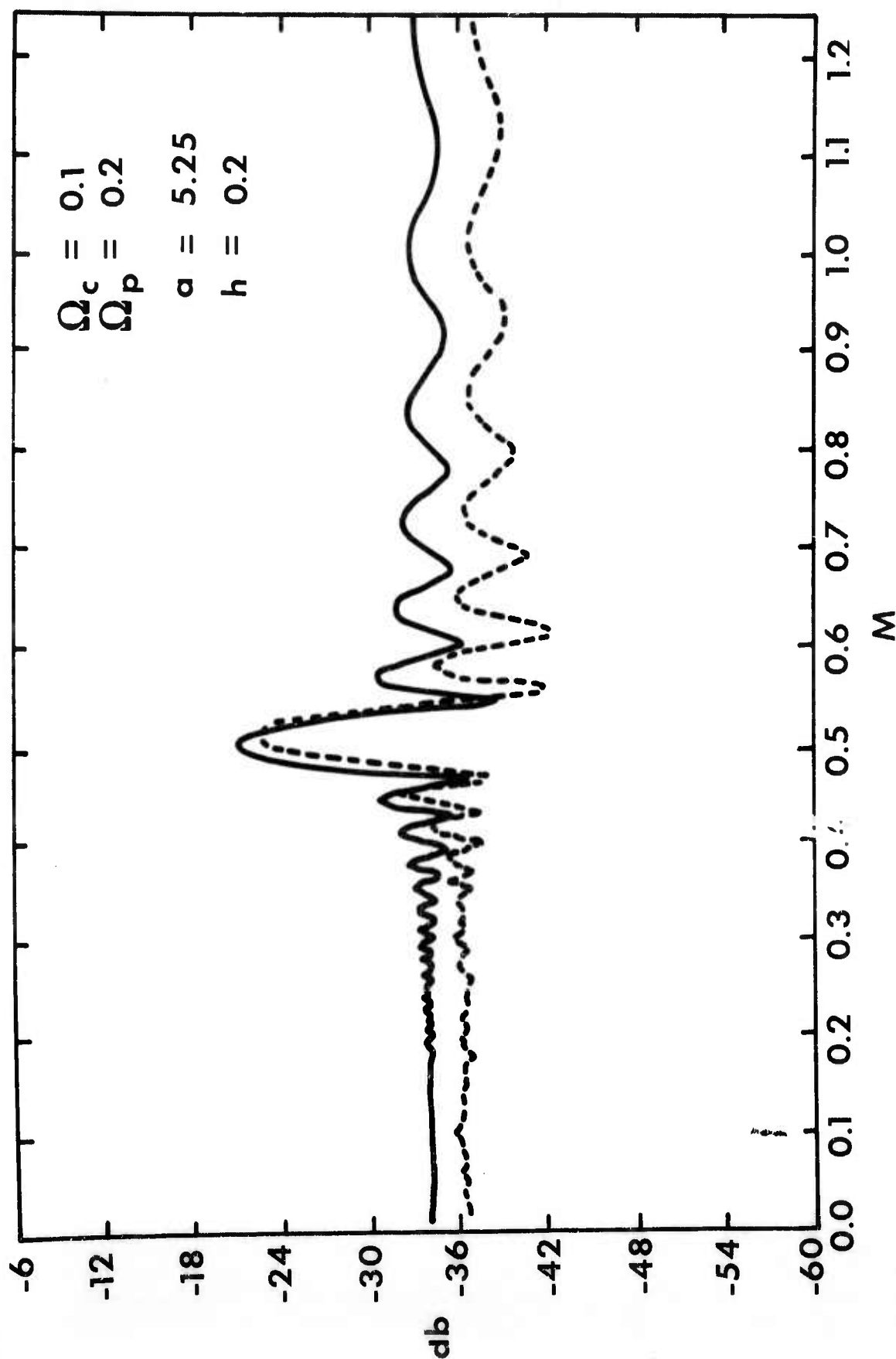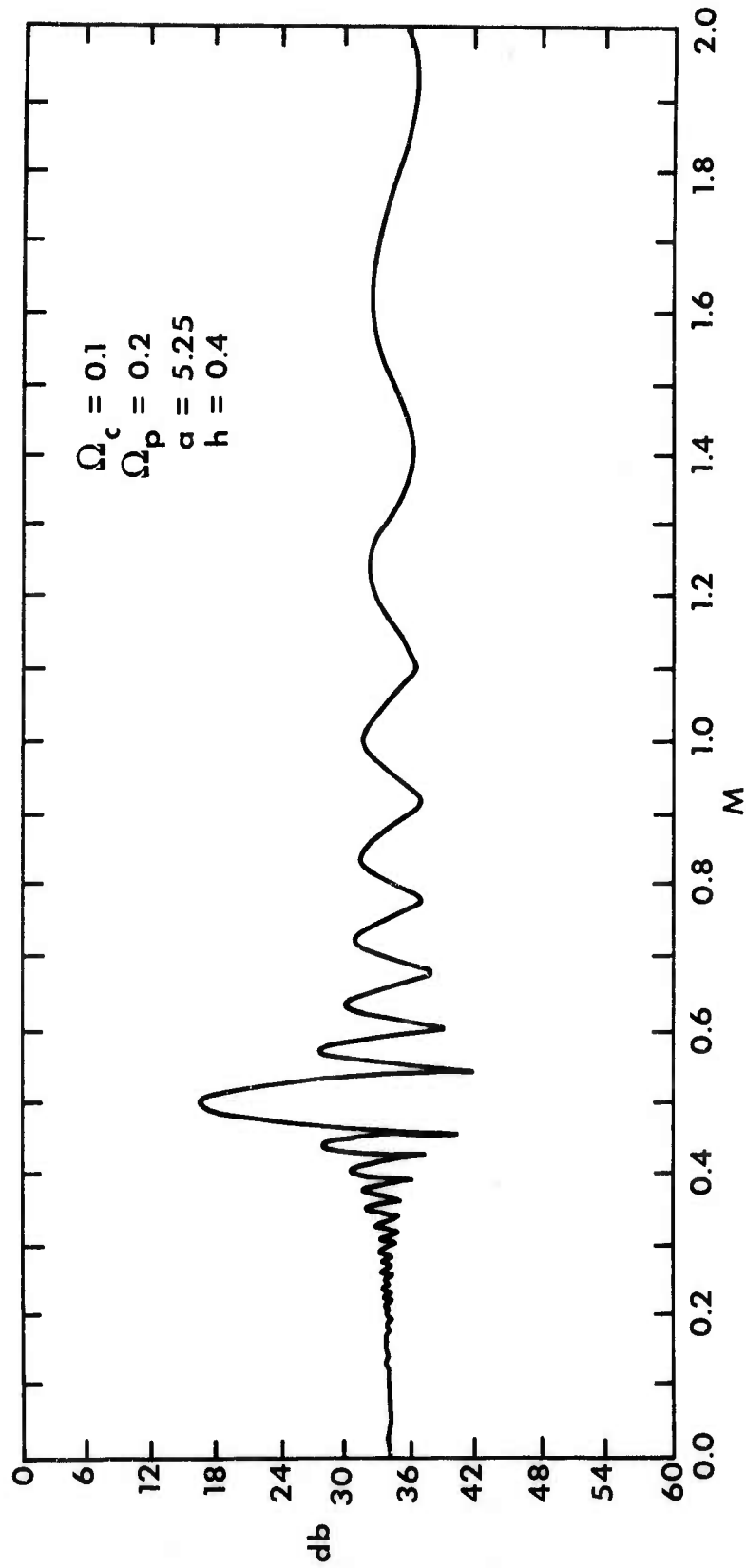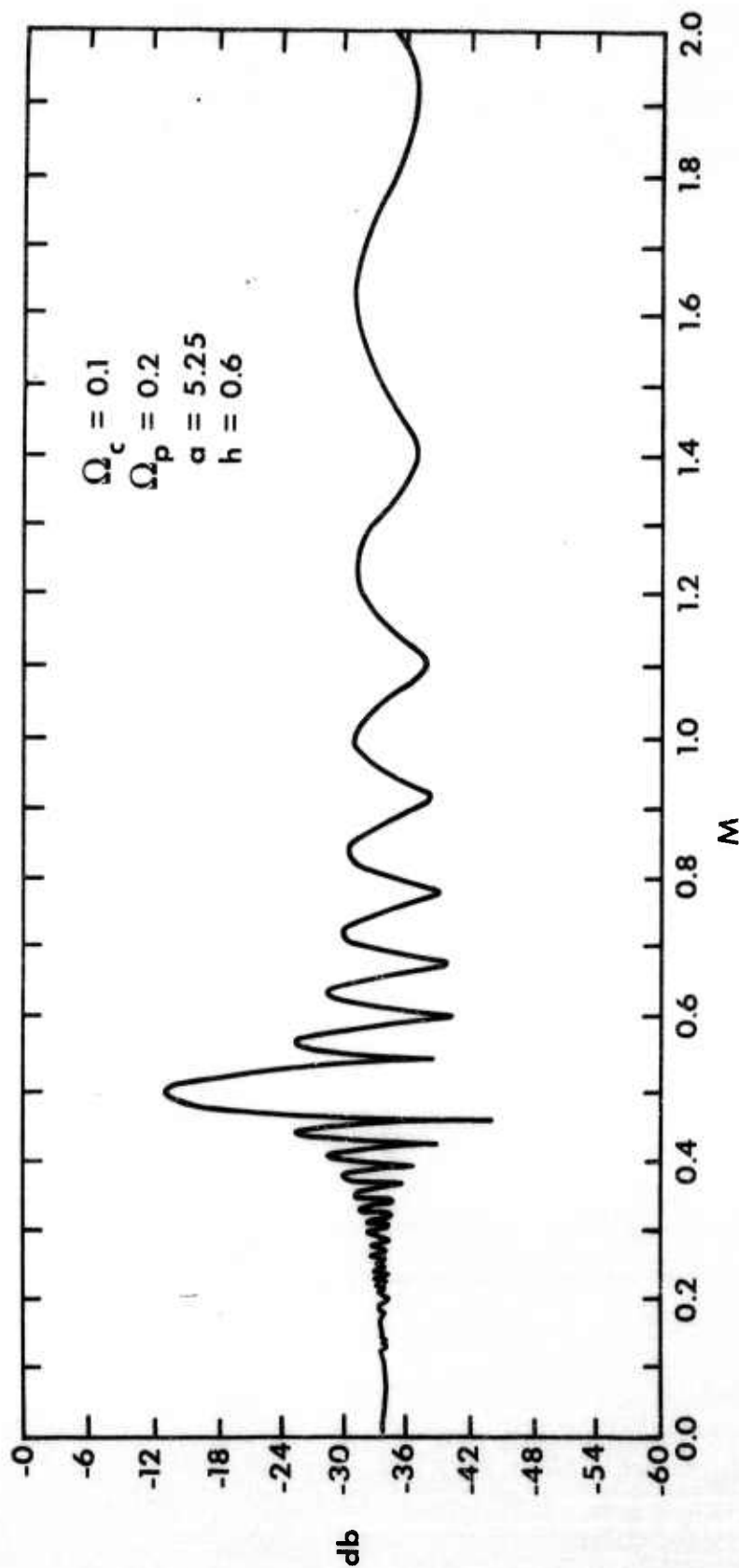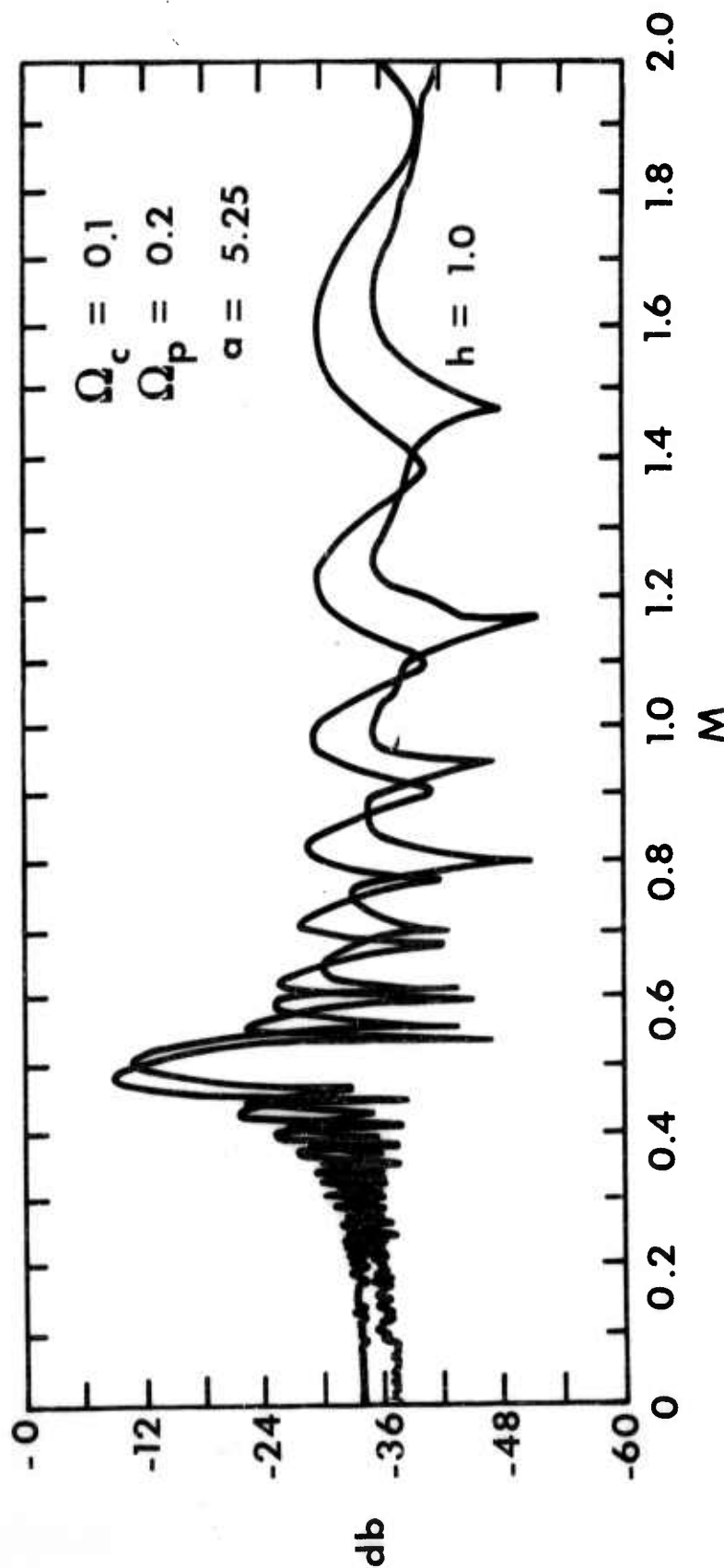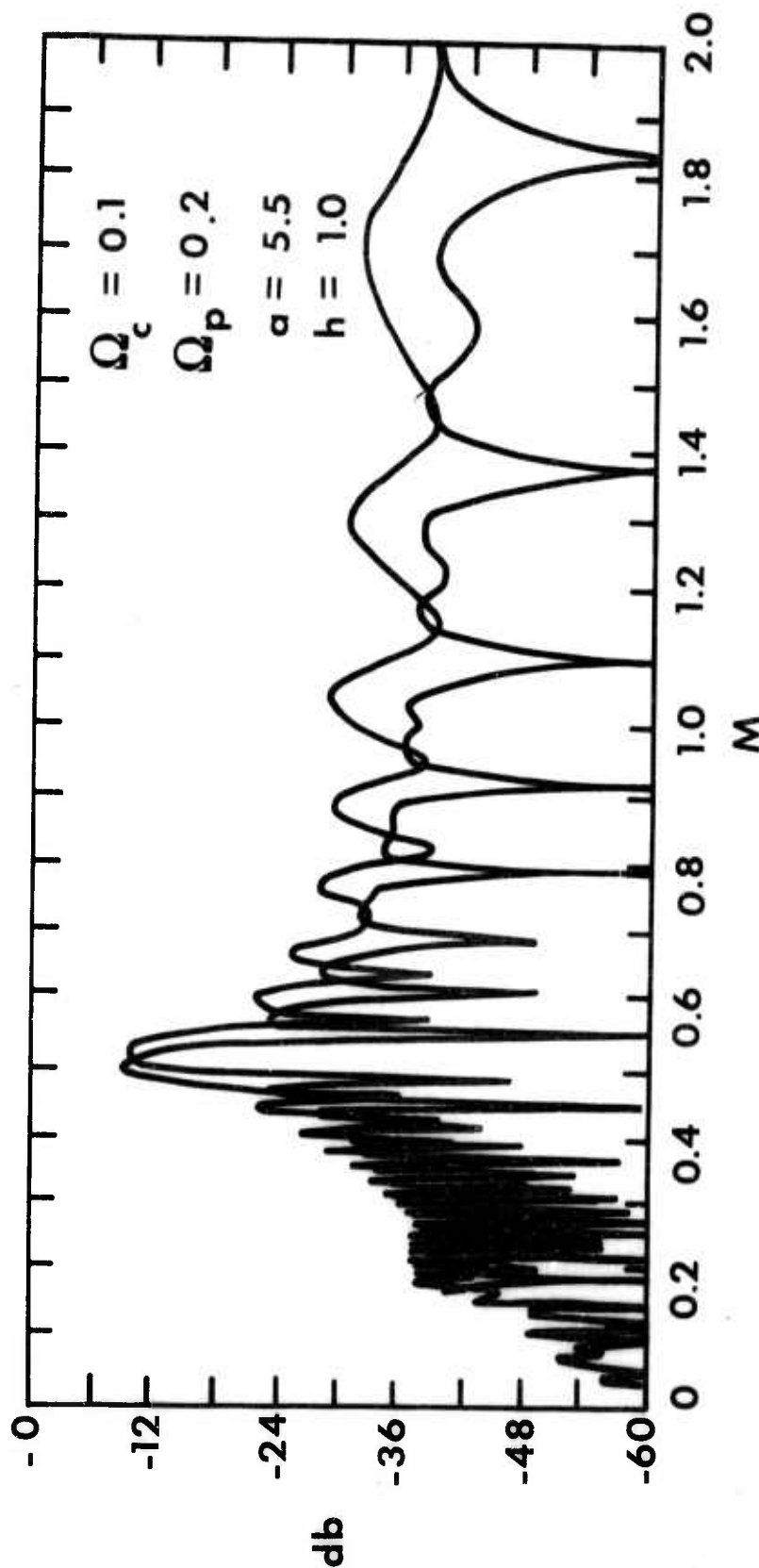Colored Curve:   Exact Values of Reflection Coefficient

Black Curve:   Born Approximation of the Reflection Coefficient

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